ETS-VII Flight Experiments For Space Robot Dynamics and Control

Theories on laboratory test beds ten years ago, Now in orbit

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Abstract: The Engineering Test Satellite VII (ETS-VII), developed and launched by National Space Development Agency of Japan (NASDA) has been successfully flown and carried out significant experiments on orbital robotics with a 2 meter-long, 6 DOF manipulator arm mounted on this un-manned spacecraft. The ETS-VII should be noted as one of remarkable outcomes of the research effort on space robots, particularly characterized as an orbital free-flying robot. This paper highlights a story how the theories have been developed mathematically, studied with laboratory test bed, then demonstrated in orbit.

1. Introduction

The ideas for the rescue and service to a malfunctioning satellite by a free-flying space robot has been discussed since early 80s (for example [1]), but very few attempts have ever done in orbit. The maintenance missions of the Hubble Space Telescope and the retrieval of the Space Flyer Unit are such important examples carried out with the Space Shuttle Remote Manipulator System. However, in these missions the manipulator was manually operated by a well-trained flight crew. Autonomous target capture by an un-manned space robot is a big challenge for space robotics community for many years, and very recently, essential parts of this technology have been successfully verified and demonstrated in orbit by a Japanese free-flying space robot, ETS-VII.

The Engineering Test Satellite VII (ETS-VII, Figure 1), developed and launched by National Space Development Agency of Japan (NASDA) in November 1997, has been successfully flown and carried out a lot of interesting orbital robotics experiments with a 2 meter-long, 6 DOF manipulator arm mounted on this un-manned spacecraft. The mission objective of ETS-VII is to test robotics technology and demonstrate its utility for un-manned orbital operation and servicing tasks. The mission consists of two subtasks, autonomous rendezvous/docking (RVD) and robot experiments (RBT). The robot experiments include a variety of topics such as: (1) teleoperation from the ground with large time-delay, (2) robotic servicing task demonstrations such as ORU exchange and deployment of a space structure, (3) dynamically

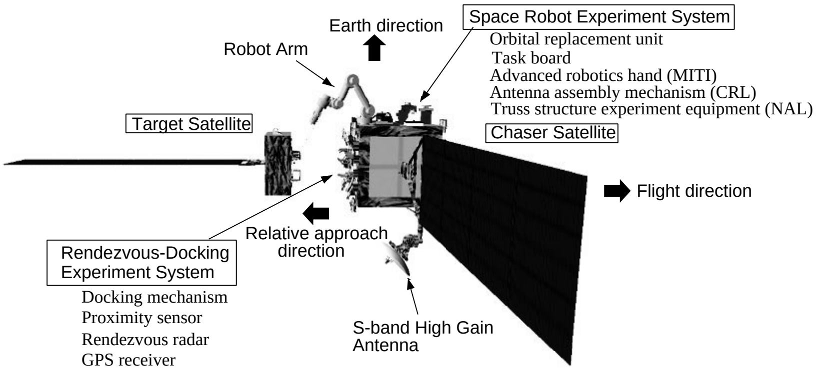


Figure 1. The Engineering Test Satellite VII

coordinated control between the manipulator reaction and the satellite attitude, and (4) capture and berthing of a target satellite. Early reports on some of these experiments were made in the paper [2] and in the proceedings [3], for example.

The initially planned flight experiments were successfully completed by the end of May 1999. But since the spacecraft was still operational in a good condition, an extensive mission period was set up till the end of December 1999. In this period the opportunity was opened for academic proposals and research groups of Japanese universities were given the time to do their flight experiments. Using this precious opportunity, the present author has proposed and carried out the experiments to highlight the motion dynamics of a free-flying space robot, verifying the theories on the coupling and coordination between the manipulator reaction and the base spacecraft attitude. Some details are already reported in [4][5][6][7].

In this paper, the focus is made on the evolution of experimental robotics effoert from simplified laboratory test beds to a real flight system in orbit. The paper is organized as follows. In section 2, the motion dynamics to characterize a free-flying space robot and concepts for the manipulation in space, originally discussed in late 80s and early 90s, are reviewed. In section 3, the laboratory test beds having been developed by the present author since 1987 are recalled. In section 4, the results of the corresponding ETS-VII flight experiments carried out in 1999 are presented. In section 5, a complementary discussion is made for future practical satellite servicing missions.

2. Dynamics of a Free-Flying Space Robot

A unique characteristics of a free-flying space robot is found in its motion dynamics. According to the motion of the manipulator arm, the base spacecraft moves due to the action-to-reaction principle or the momentum conservation.

The reaction of the arm disturbs its footing base, then the coupling and coordination between the arm and the base becomes an important issue. This is a main difference from a terrestrially based robot manipulator and a drawback to make the control of a space manipulator difficult. Earlier studies for the modeling and control of such a free-flying robot are collected in the book [8]. Here the basic modeling is reviewed to derive the key concepts named the generalized Jacobian matrix and the reaction null-space.

2.1. Basic equations

The equation of motion of a free-flying space robot as a multibody system is, in general, expressed in the following form:

$$\begin{bmatrix} \boldsymbol{H}_b & \boldsymbol{H}_{bm} \\ \boldsymbol{H}_{bm}^T & \boldsymbol{H}_m \end{bmatrix} \begin{bmatrix} \ddot{\boldsymbol{x}}_b \\ \ddot{\boldsymbol{\phi}} \end{bmatrix} + \begin{bmatrix} \boldsymbol{c}_b \\ \boldsymbol{c}_m \end{bmatrix} = \begin{bmatrix} \mathcal{F}_b \\ \boldsymbol{\tau} \end{bmatrix} + \begin{bmatrix} \boldsymbol{J}_b^T \\ \boldsymbol{J}_m^T \end{bmatrix} \mathcal{F}_h \tag{1}$$

where we choose the linear and angular velocity of the base satellite (reference body) $\dot{\boldsymbol{x}}_b = (\boldsymbol{v}_b^T, \boldsymbol{\omega}_b^T)^T$ and the motion rate of the manipulator joints $\dot{\boldsymbol{\phi}}$ as generalized coordinates. The symbols used here are defined as follows:

$\boldsymbol{H}_b \in R^{6\times 6}$: inertia matrix of the base.

$\boldsymbol{H}_m \in R^{n\times n}$: inertia matrix for the manipulator arms (the links except the base.)

$\boldsymbol{H}_{bm} \in R^{6\times n}$: coupling inertia matrix.

$\boldsymbol{c}_b \in R^6$: velocity dependent non-linear term for the base.

$\boldsymbol{c}_m \in R^6$: that for the manipulator arms.

$\mathcal{F}_b \in R^6$: force and moment exert on the centroid of the base.

$\mathcal{F}_h \in R^6$: those exert on the manipulator hand.

$\boldsymbol{\tau} \in R^n$: torque on the manipulator joints.

Especially in the free-*floating* situation, the external force/moment on the base which can be generated by gas-jet thrusters, and those on the manipulator hand are assumed zero; i.e. $\mathcal{F}_b = \mathbf{0}$, $\mathcal{F}_h = \mathbf{0}$. The motion of the robot is governed by only internal torque on the manipulator joints $\boldsymbol{\tau}$, and hence the linear and angular momenta of the system $(\mathcal{P}^T, \mathcal{L}^T)^T$ remain constant.

$$\begin{bmatrix} \mathcal{P} \\ \mathcal{L} \end{bmatrix} = \boldsymbol{H}_b \dot{\boldsymbol{x}}_b + \boldsymbol{H}_{bm} \dot{\boldsymbol{\phi}} \tag{2}$$

2.2. Angular momentum

The integral of the upper set of the equation (1) gives the momentum conservation, as shown in Equation (2), which is composed of the linear and angular momenta. The linear momentum has further integral to yield the principle that the mass centroid stays stationary or linearly moves with a constant velocity.

The angular momentum equation, however, does not have the second-order integral hence provides the first-order non-holonomic constraint. The equation is expressed in the form with the angular velocity of the base $\boldsymbol{\omega}_b$ and the motion rate of the manipulator arm $\dot{\boldsymbol{\phi}}$ as:

$$\tilde{\boldsymbol{H}}_b\boldsymbol{\omega}_b + \tilde{\boldsymbol{H}}_{bm}\dot{\boldsymbol{\phi}} = \mathcal{L} \tag{3}$$

where $\mathcal{L}$ is the initial constant of the angular momentum, and the inertia matrices with tilde are those modified from Equation (2). $\tilde{\boldsymbol{H}}_{bm}\dot{\boldsymbol{\phi}}$ represents the angular momentum generated by the manipulator motion. These equations of (2) and (3) provide a basis for further discussion.

2.3. Generalized Jacobian Matrix (GJM)

The velocity of the manipulator hand in the inertial frame is expressed as:

$$^{(i)}\dot{\boldsymbol{x}}_h = \boldsymbol{J}_m\dot{\boldsymbol{\phi}} + \boldsymbol{J}_b\dot{\boldsymbol{x}}_b \tag{4}$$

Then an idea came to combine it with (2), to yield the equation directly connect the manipulator joints and hand with canceling out the base variables:

$$^{(i)}\dot{\boldsymbol{x}}_h = \boldsymbol{J}_g\dot{\boldsymbol{\phi}} \tag{5}$$

$$\boldsymbol{J}_g = \boldsymbol{J}_m - \boldsymbol{J}_b\boldsymbol{H}_b^{-1}\boldsymbol{H}_{bm} \tag{6}$$

where $(\mathcal{P}^T, \mathcal{L}^T)^T = \boldsymbol{0}$ is assumed for simplification. The matrix $\boldsymbol{J}_g$ is termed *Generalized Jacobian Matrix (GJM)*[9], and with using it the manipulator hand can be operated by resolved motion-rate control or resolved acceleration control properly in the inertial space, while allowing the base reaction but not disturbed by it.

2.4. Reaction Null-Space (RNS)

From a practical point of view, the attitude change is not desirable, then the manipulator motion planning methods to have minimum attitude disturbance on the base are also studied. An ultimate goal of those approaches is completely zero disturbance, and such operation is possible from the insight of the angular momentum equation.

The angular momentum equation with zero initial constant $\mathcal{L} = \boldsymbol{0}$ and zero attitude disturbance $\boldsymbol{\omega}_b = \boldsymbol{0}$:

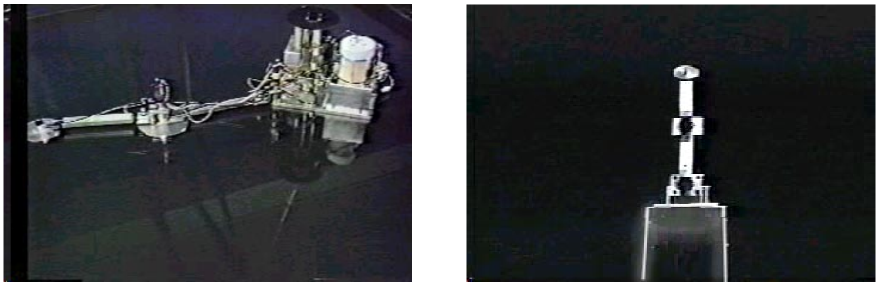
$$\tilde{\boldsymbol{H}}_{bm}\dot{\boldsymbol{\phi}} = \boldsymbol{0} \tag{7}$$

yields the following null-space solution:

$$\dot{\boldsymbol{\phi}} = (\boldsymbol{I} - \tilde{\boldsymbol{H}}_{bm}^{+}\tilde{\boldsymbol{H}}_{bm})\dot{\boldsymbol{\zeta}} \tag{8}$$

The joint motion given by this equation is guaranteed to make zero disturbance on the base attitude. Here the vector $\dot{\boldsymbol{\zeta}}$ is arbitrary and the null-space of the inertia matrix $\tilde{\boldsymbol{H}}_{bm}$ is termed *Reaction Null-Space (RNS)* [10].

The degrees of freedom for $\dot{\boldsymbol{\zeta}}$ is $n-3$, and in ETS-VII the manipulator arm has 6 DOF, i.e. $n = 6$, then there remains 3 DOF for the reaction null-space



(a) The experimental free-floating robot simulator, EFFORTS (1987)

(b) The experimental flaxible-base manipulator TREP (1996)

Figure 2. Laboratory test beds for space manipulator systems

to be specified by additional criteria. In the flight experiment presented later, a criterion is chosen that the orientation of the manipulator hand (3 DOF) is constraint, while the translation of the hand (3 DOF) is allowed in realizing the zero reaction on the base. This manipulator motion is termed the *reactionless manipulation.*

3. Laboratory Test Beds

3.1. EFFORTS

EFFORTS is the **E**xperimental **F**ree-**F**l**O**ating **R**obo**T** **S**atellite simulator developed since 1987 (Figure 2(a)) [11], which is one of the earliest attempts of air-cushion type microgravity test beds. The robot model is floated by pressurized air on a horizontal planar table. The motion is constraint on a plane though, the test bed is very useful to study the reaction dynamics of an articulated link systems and effective to demonstrate the performance of the GJM based inertial manipulation in the microgravity environment. The test bed well contributed to appeal the importance of the reaction effect in space manipulation.

3.2. TREP

TREP is a test bed comprising rigid articulated manipulator arm(s) mounted at the end of a flexible beam (Figure 2(b))[10]. The flexible beam has a parallel double-beam structure to allow the bending deformation on a horizontal plane, while the deformations in other directions are restricted. Using this test bed the manipulation that yields zero reaction to a certain direction of the base, as well as the effective vibration suppression control by the manipulator motion have been studied. A number of primitive experiments for the RNS based reactionless manipulation have been carried out with this test bed [12].

4. ETS-VII Flight Experiments

The robotic flight experiment proposed by the present author was carried out on September 30, 1999, using three successive flight paths. The flight path is a communication window between Tsukuba Space Center, NASDA, and ETS-VII via TDRS, a US data relay satellite located in the geosynchronous orbit above the pacific ocean. In each path almost net 20 minutes operation (command uplink) and dense telemetry (including video downlink) are established.

The purpose and also the advantage of the flight experiments using a real space system is to obtain the proof of the theories that are suggested only by confined laboratory test beds, and to demonstrate the practical availability of the methods in real world. However the difficulty is that practical systems always have many constraints and restrictions from design specification and safety point of view. For example, the manipulator arm mounted on ETS-VII is a 6 DOF non-redundant arm. If it would be a redundant one, we could demonstrate a wide range of interesting performances. But the present system is still good enough to show the basic performance of the proposed concepts. In operation, it is very difficult to implement a newly proposed control algorithm into the existing on-board computers and test the closed-loop performance. But the open-loop type control experiments were accepted in ETS-VII.

For the proposed experiment, the manipulator motion trajectories were carefully prepared in a motion file and the safety was preliminary checked on an offline simulator. During the experiment, the motion file is uploaded to ETS-VII at 4 Hz frequency as an isochronous command and the manipulator arm is controlled to follow the prepared motion profile. In preparing the motion profile, best knowledge on the inertia parameters of the system was used, which were elaborately identified with the flight telemetry data obtained until May 1999.

4.1. GJM Based Inertial Manipulation

For the GJM based inertial manipulation, the experiment was carried out under the free-floating environment without any base attitude control actions or zero initial momentum in the system.

Figure 3 depicts the experimental flight data for the GJM based manipulation. The motion demonstrated here is straight-path tracking in the inertial frame, under the resolved motion-rate control with the generalized Jacobian using the inversion of Equation (5). The top graph shows a profile for the pitch angle of the manipulator hand in the satellite base frame. The middle shows the pitch attitude of the base satellite, disturbed by the manipulator reaction. The bottom is the summation of the top and the middle graphs, then represents the attitude of the manipulator hand in the inertial frame. By means of the control with the generalized Jacobian, the attitude of the hand in the inertial frame is kept almost zero against a non-negligible satellite attitude disturbance.

Figure 4 campares the performance to reach a given point in the inertial frame such as a free-floating target. The graph depicts the error distance between the hand and the target. The broken line shows the flight data to capture a floating target by the manipulator control without GJM. Without GJM the hand moves to incorrect direction, but the error is corrected by means of visual servo-tracking, then finally the capture is attained. However with GJM, as shown in the solid line, the target capture is attained earlier because

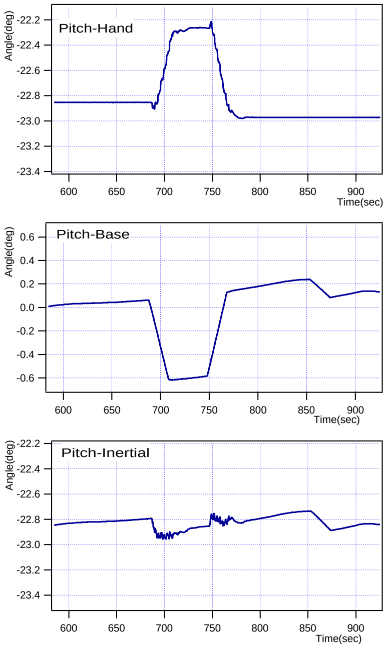


Figure 3. ETS-VII flight data for the GJM based inertial manipulation

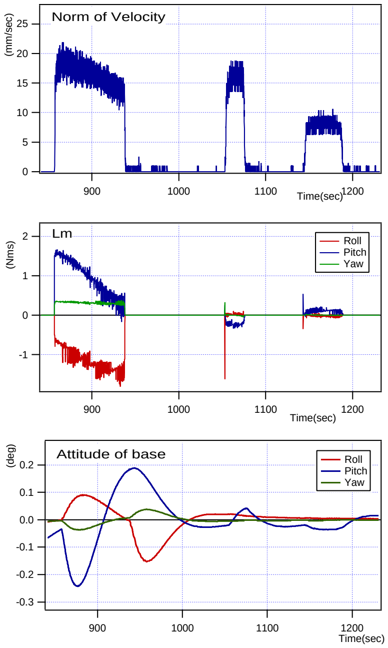


Figure 5. ETS-VII flight data for the RNS based reactionless manipulation

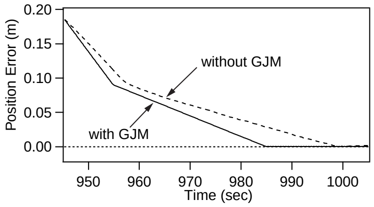


Figure 4. Comparison of the approaching performance to an inertially-floating target, between with and without GJM

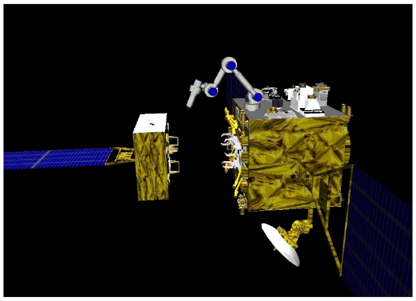


Figure 6. A computer graphic image for the target capture simulation

the hand moves toward the target exactly straightly.

4.2. RNS based reactionless manipulation

In the RNS experiment, several sets of reactionless trajectories were prepared based on the reaction null-space formulation. We prepare the trajectories to go to or from useful control points such as an onboard ORU or a target satellite, and compared with the motion by conventional PTP trajectories.

The experiment was carried out under the attitude control of the base satellite using reaction wheels. Even under the control, the attitude disturbance is observed when the base receives the manipulator reaction, since the control torque of reaction wheels is relatively small. The attitude control here mainly works for the recovery after the attitude disturbed.

Figure 5 depicts a typical flight data to compare the conventional and reactionless manipulations. The top graph shows the velocity norm of the manipulator hand. The middle shows the reaction momentum induced by the manipulation. And the bottom shows the attitude motion. The graphs include three sets of manipulator motion, where the first one is the conventional PTP manipulation generating a relatively large momentum and attitude disturbance, while the other two are the RNS based reactionless manipulation yielding very small, almost zero reaction and disturbance.

It should be noted that, not only the maximum attitude change is remarkably small, but the time for the recovery is also very short with the reactionless manipulation. This waiting time for the attitude recovery in the conventional manipulation is not negligible and degrade the efficiency of the operation in practice. However, the reactionless manipulation provides almost zero attitude disturbance and almost zero recovery time, thus assuring a very high operational efficiency.

5. Toward Practical Satellite Servicing

In the ETS-VII flight experiments, a whole sequence of the capture of a free-floating target was not demonstrated continuously, however, all necessary key elements were verified each by each. The technology necessary for the orbital maneuver in approaching to a target, rendezvous and precise proximity flight control has been successfully demonstrated with the ETS-VII's main satellite (chaser) and a target satellite separated from the chaser. Three different flight paths called FP-1, 2 and 6, including contingency maneuvers, were tested and all resulted in autonomous soft-docking safely [13].

For the target capture, not for docking, a manipulator arm should be operated to track and grasp a fixture mounted on the target satellite, while maintaining the proximity flight with the target. One of the key technology is the visual servo-tracking of the grasping point by the manipulator arm. This was successfully tested with a set of CCD camera mounted on the manipulator hand and an optical marker located at the target fixture, using on-board real-time video signal processing.

Further control technology to improve the manipulator control, and thereby increase the fidelity and safe margin of the successful capture, were also tested and important flight data were obtained. They are GJM based inertial manipulation and RNS based reactionless manipulation, as presented above.

The reactionless manipulation is an idea to operate the manipulator arm while not disturbing the base satellite attitude. Such manipulator trajectories are very limited in case of a 6 DOF arm although, they are proven very effective to minimize the base attitude disturbance and save time to wait for the attitude recovery. The RNS based reactionless manipulation should be useful for coarse approach to the target under the proximity flight, where the attitude disturbance due to the manipulator reaction is highly undesirable.

During the final approach with visual servoing, the manipulator hand must be controlled for the target floating in the inertial frame. In this phase the GJM based inertial manipulation, which is also proven effective in practical situation, should be particularly useful.

For practical satellite capture operation expected in near furure, it will be therefore a best combination of technology to make the coarse approach with the proximity flight control of the spacecraft and the RNS based reactionless manipulation of the arm, then switch to the final approach with the visual-servo tracking and the GJM based inertial manipulation of the hand while the spacecraft is left under free-drift until finally captured.

Post flight analysis and computer simulatuions (Figure 6) are now extensively continuing with possible assumptions for a practical satellite servicing mission. The analysis suggests that the introduction of a redundant arm, with 7 DOF or more, will enhance the advantage and performance of the RNS based reactionless manipulation [14].

6. Conclusions

This paper presents a story about the development of the space robot dynamics and control technology. The Generalized Jacobian Matrix (GJM) based inertial manipulation and the Reaction Null-Space (RNS) based reactionless manipulation have been theoretically studied since middle 80s and their preliminary verifications have been done with simplified and confined laboratory test beds. Finally the theories are evaluated in the practical performance by the flight demonstration of a real space robot in orbit.

Both of GJM and RNS based control concepts are successfully verified on ETS-VII, as well as other technology relevant to the target capture such as the rendezvous control and the visual servo-tracking of the manipulator hand. A whole sequence of the autonomous target capture was not demonstrated in orbit although, it is analytically inferred by post flight analysis. From the flght data, the GJM based inertial manipulation is verified with higher performance to reach a given point in the inertial frame such as a free-floating target. Also, the RNS based reactionless manipulation verified with almost zero attitude disturbance and almost zero recovery time, thus assuring a very high operational efficiency.

The ETS-VII opened a very solid way to the autonomous target capture. We hope that these technologies are further improved and applied to practical missions for satellite servicing or robotic rescue.

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